Dark Matter and Dark Radiation

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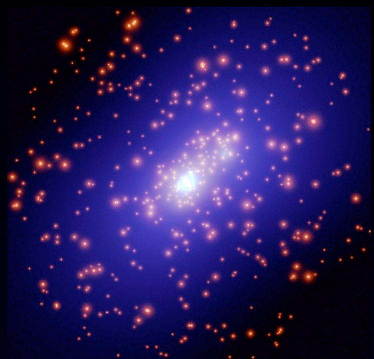
arXiv:0810.5126

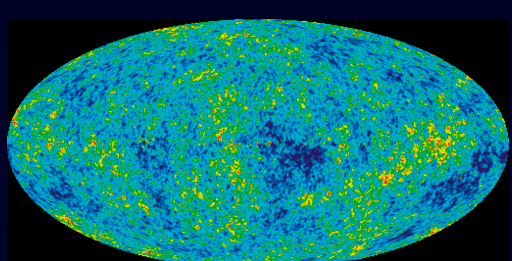
What do we know about Dark Matter?



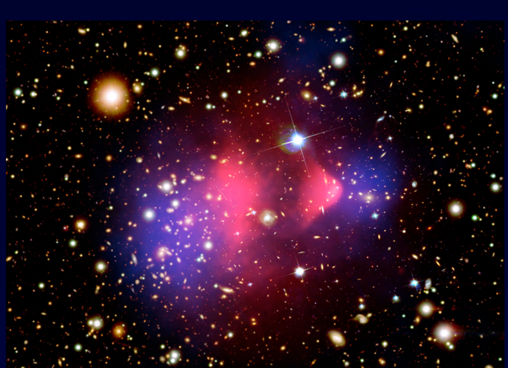
Interacts with gravity

Stable or very long lived

Dark: weak coupling to photons



23% of energy of the Universe in cold dark matter $\Omega_{\mathrm{CDM}} h^2 = 0.106 \pm 0.008$



DM-DM interactions small

WIMP: stable, neutral particle with weak scale couplings and mass

- Thermal relic, freezes out when $\Gamma_{ann} \sim H$

$$\Omega_{\rm CDM} h^2 \sim \frac{10^{-10}{\rm GeV}^{-2}}{< \sigma v >}$$

For $m_{\rm weak} \sim 10^{2-3}{\rm GeV}$ and $g_{\rm weak} \sim 0.6$

$$< \sigma v > \sim \frac{g_{\rm weak}^4}{m_{\rm weak}^2} \rightarrow \Omega_{\rm CDM} h^2 \sim 0.1$$

- Connection between DM and particle physics: SUSY, extra dimensions,...

WIMPs are compelling Dark Matter Candidates!

But...

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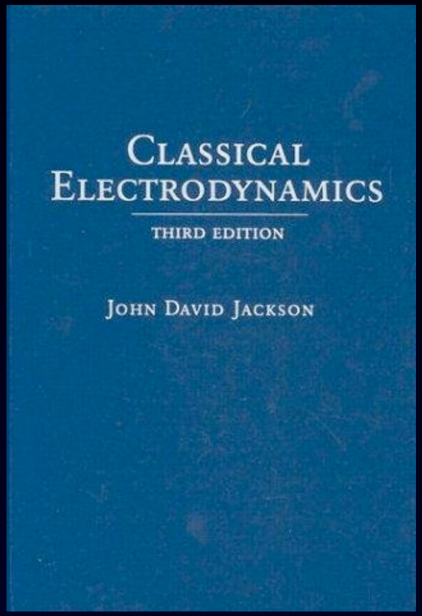
But...

Could we have "Dark Electromagnetism"?

with M. Buckley, S. Carroll, M. Kamionkowski arXiv:0810.5126

- Dark Matter sector consists of (fermionic) DM χ and "dark photons" $\hat{\gamma}$



Why would Dark E&M be interesting?

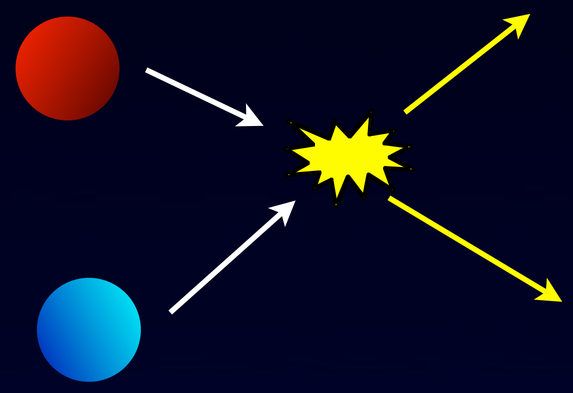
A U(1) gauge symmetry protects the mass of the dark photon $\Longrightarrow$ Natural long-range force!

Why didn't people think of it before?

- The Universe should have a zero net charge

- Equal number of positive and negative charges

- Then, all the dark matter should annihilate away!



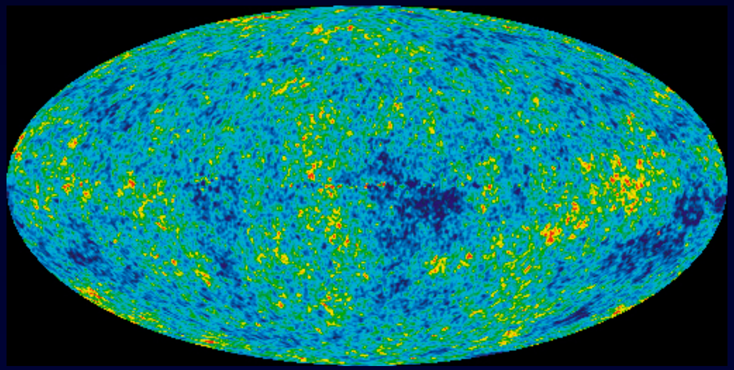
But, if the DM number density is low enough they wouldn't find each other and wouldn't annihilate

Dark Matter Relic Abundance

Dark electromagnetism has two parameters:

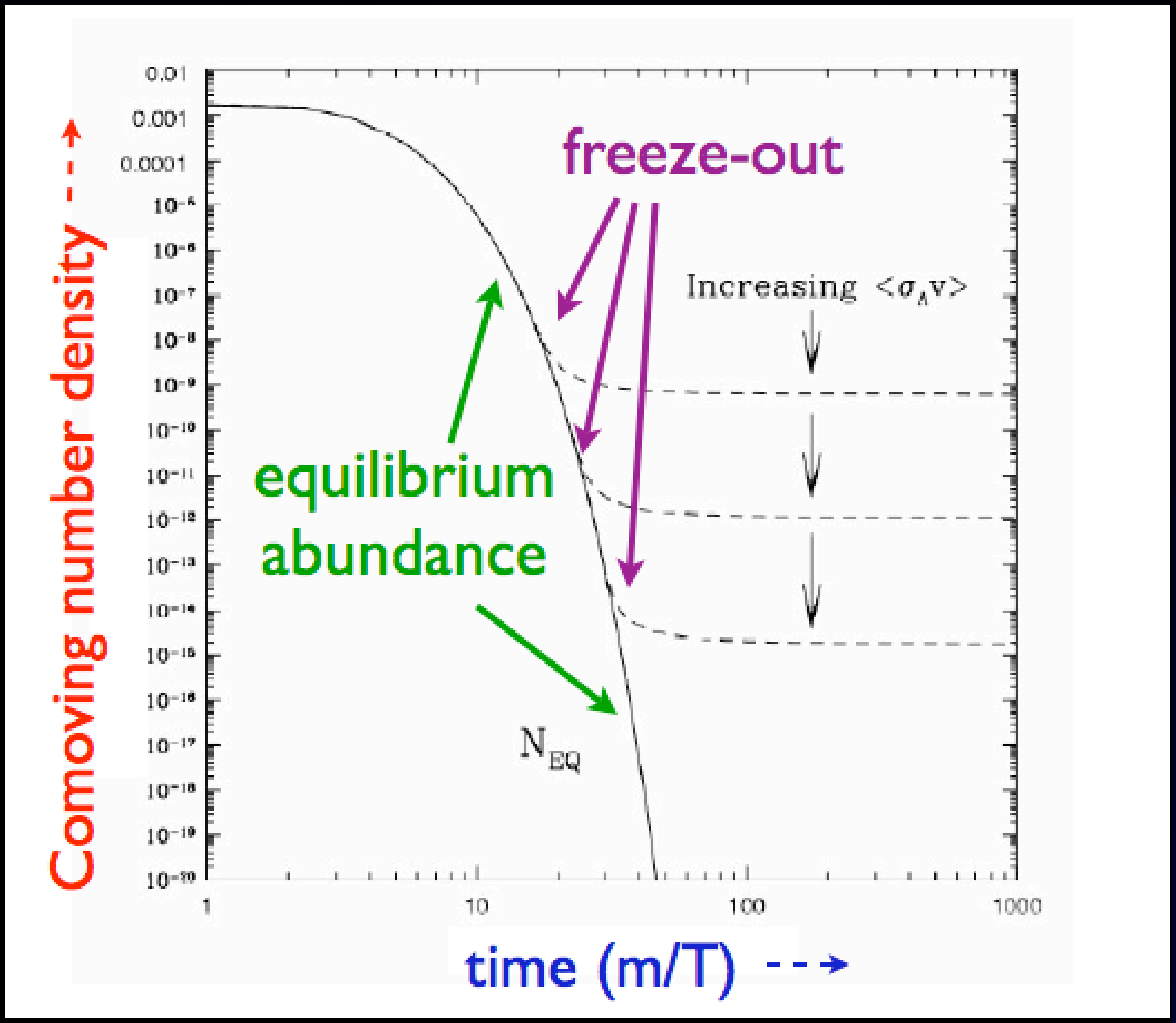
- Mass of DM particle m_χ
- Dark fine-structure constant $\hat{\alpha} = \frac{\hat{e}^2}{4\pi}$

Given m_χ what value of $\hat{\alpha}$ gives the correct relic abundance?



$$\Omega_{\rm CDM} h^2 = 0.106 \pm 0.008$$

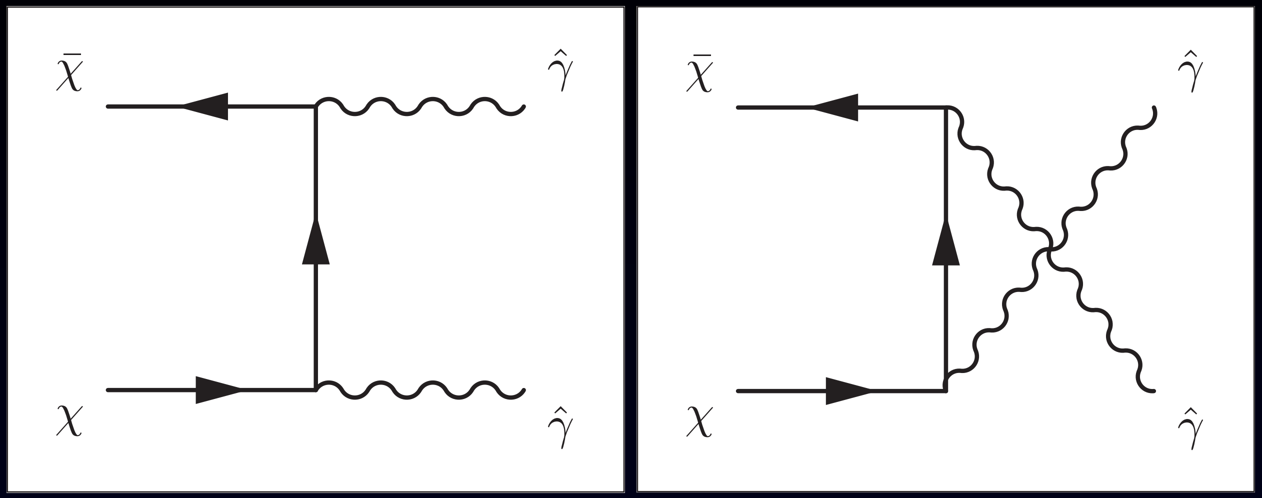
freeze-out $\Gamma_{annh} \sim H$



$$\Omega_{\rm DM} h^2 = 1.07 \times 10^9 \frac{(n+1) x_f^{n+1}\ {\rm GeV}^{-1}}{(g_{*\rm S}/\sqrt{g_*}) m_{\rm Pl} < \sigma v >}$$

$$x_f = m/T_f \approx 25$$

DM in equilibrium through annihilation to $\hat{\gamma}$

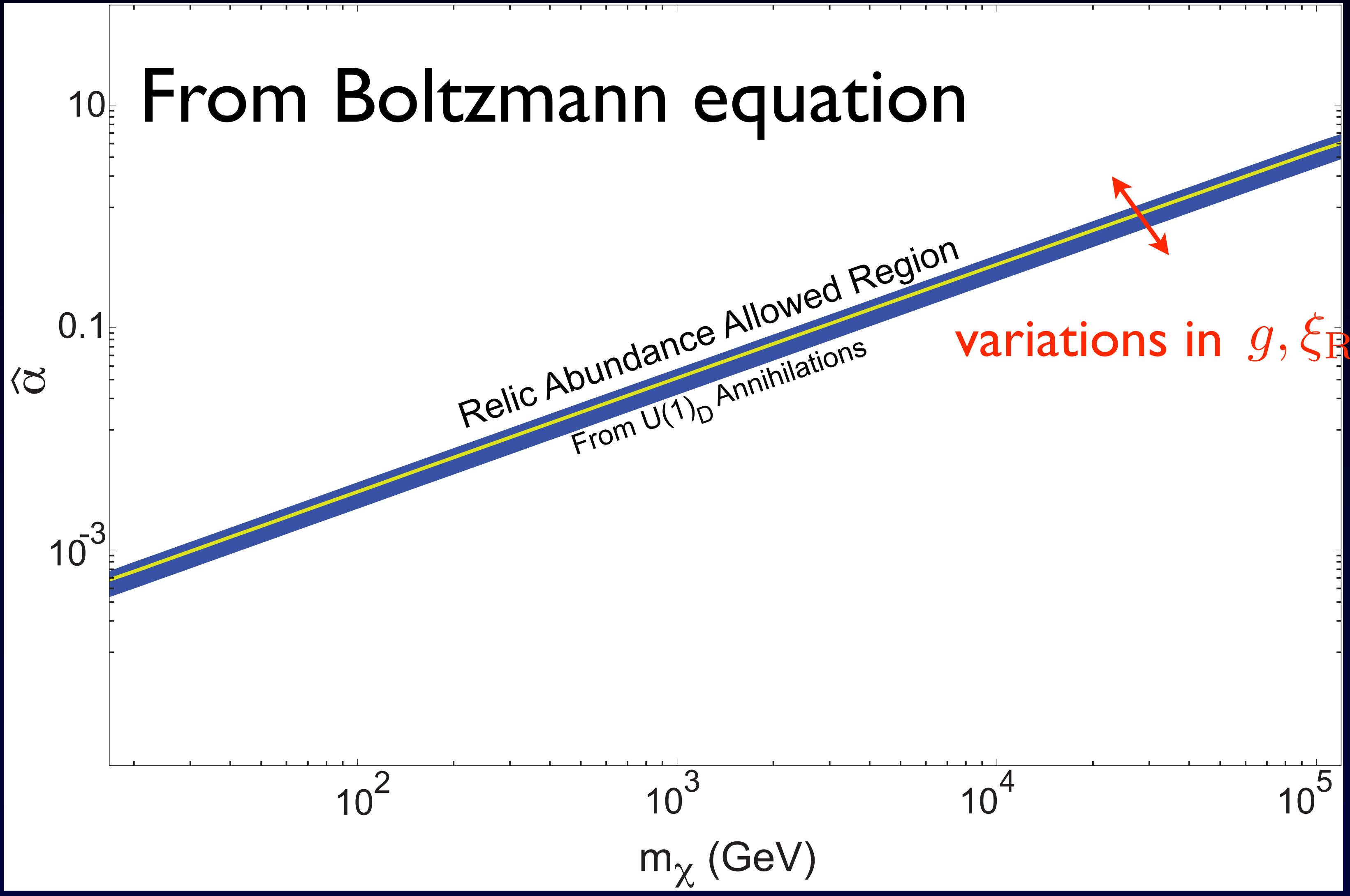


$$\langle \sigma v \rangle \approx \sigma_0 = \frac{\pi \hat{\alpha}^2}{2 m_\chi^2} + \mathcal{O}(v^2)$$

For TeV-scale DM

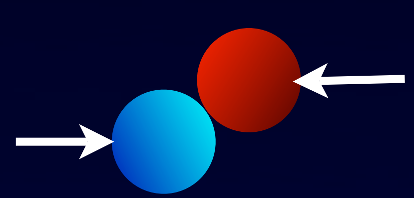
$$\hat{\alpha} \sim 10^{-2}$$

$$\left(< \sigma v > \sim \frac{\hat{\alpha}^2}{m_\chi^2} \sim \frac{g^4}{m_W^2} \right)$$

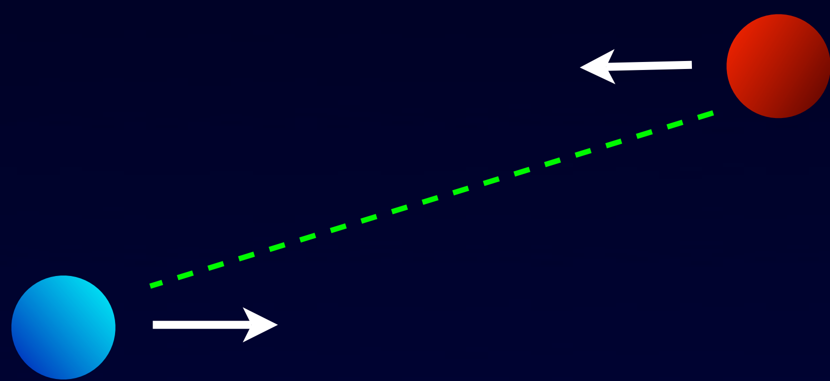


What is different about having a $U(1)_D$?

- Halo is $U(1)_D$ neutral
- Can have long-range interactions between $\chi/\bar{\chi}$
  - Scattering cross-section at low-velocities: $\sigma \propto v^{-4}$ relevant for galactic dynamics, but irrelevant for early universe annihilations

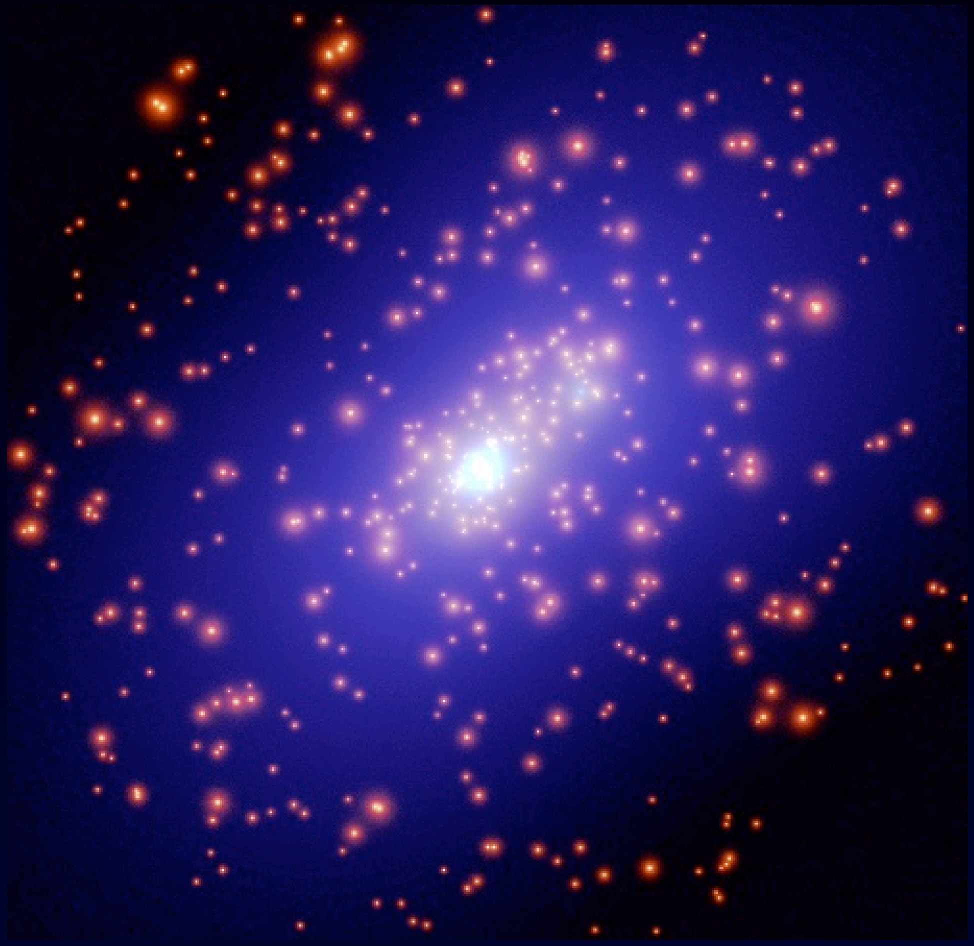


Short-range force



long-range force

Is DM collisionless or is collisionless a  ?

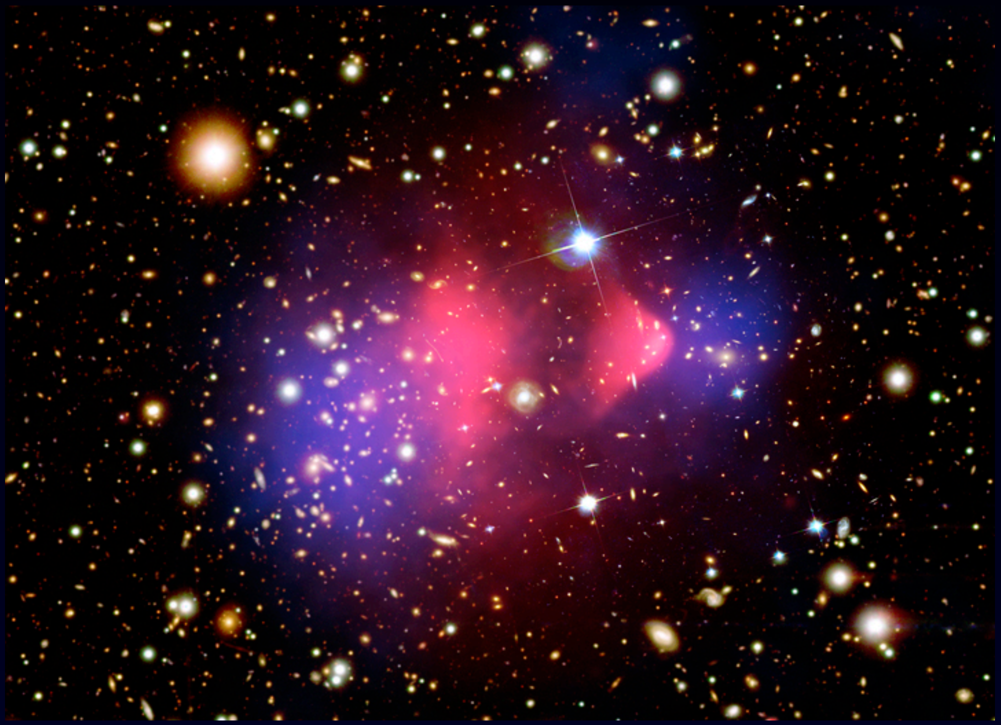


DM in cluster CL0024+1654 [Kneib, Ellis & Treu]

Baryons collide, loose energy and settle down

DM remains dilute

Bullet Cluster



[Clowe et al.]

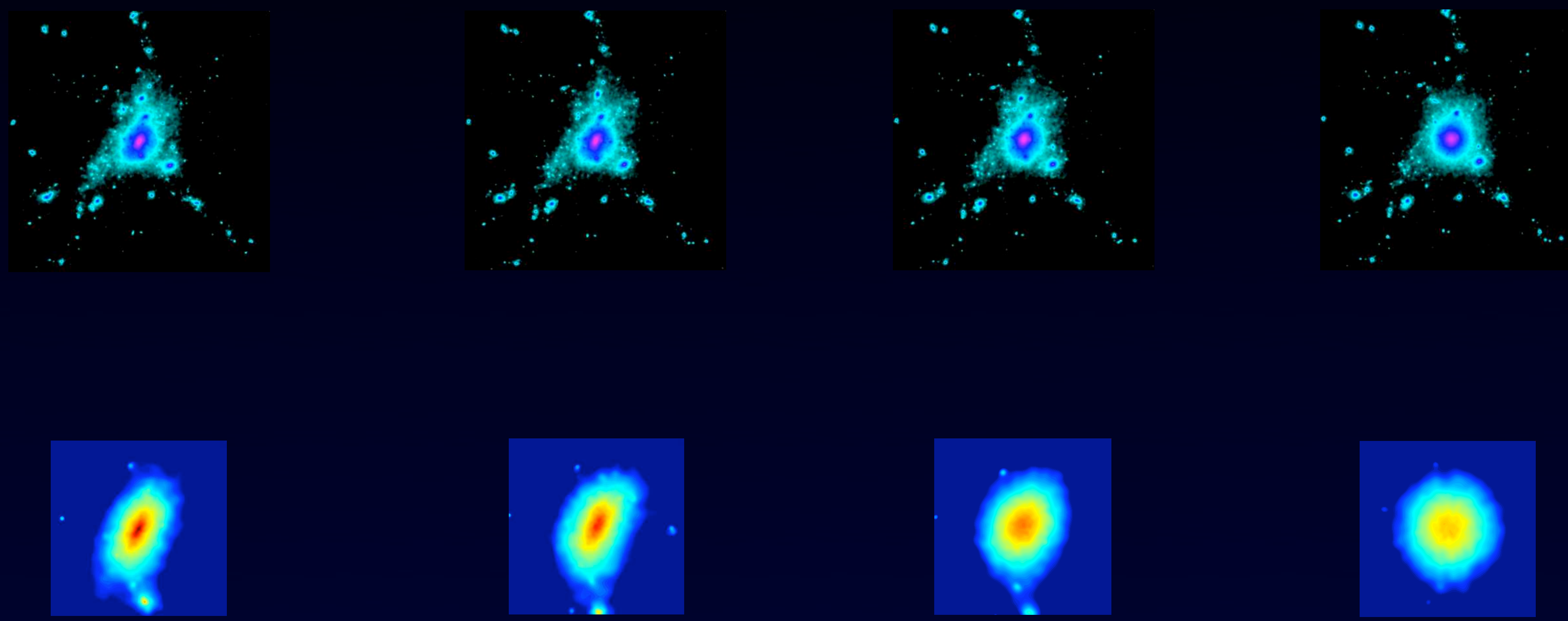
- Collisional gas slowed
- “Collisionless” DM passes trough

$$\sigma/m \leq 1.25\,\mathrm{cm}^2/\mathrm{g} \approx 2\times 10^{12}\,\mathrm{pb}/\mathrm{GeV}$$

WIMPs $\frac{\alpha^2}{m_W^3} \sim 10^{-14}\mathrm{cm}^2/\mathrm{g}$

Increase collisions DM $\longrightarrow$ less cuspy cores and more spherical haloes

Simulated clusters and their cores:



$\sigma/m = 0$ $\quad$ $\sigma/m = 0.1\,\mathrm{cm}^2/\mathrm{g}$ $\quad$ $\sigma/m = 1\,\mathrm{cm}^2/\mathrm{g}$ $\quad$ $\sigma/m = 10\,\mathrm{cm}^2/\mathrm{g}$

[Yoshida et al.]

There are suggestions that a $\sigma/m \neq 0$ is preferred by simulations

Less cuspy cores, less # dwarf galaxies $\sigma/m \sim 0.5 - 5\mathrm{cm}^2/\mathrm{g}$

- Possibly too much interaction: lensing study from cluster shows ellipticity of DM distribution $\sigma/m < 0.05\,\mathrm{cm}^2/\mathrm{g}$ [Miralda-Escude]

We take the limit to be 1 hard scattering per DM in the Galactic halo per 10^{10} years

time between collisions

$$\Longrightarrow \qquad \sigma/m \lesssim 0.3\,\mathrm{cm}^2/\mathrm{g}$$

$$\tau = \frac{1}{n\sigma v}$$

$$\rho = n m_\chi = 0.3\,\mathrm{GeV}/\mathrm{cm}^3$$

$$v/c = 10^{-3}$$

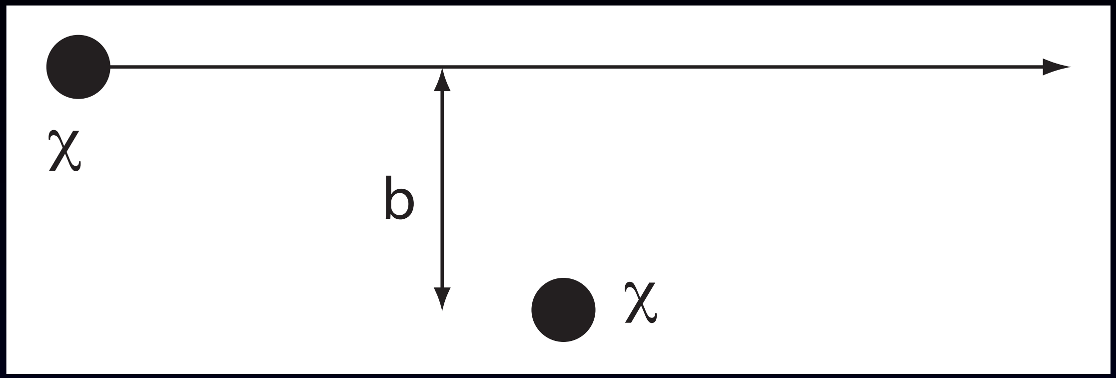
Galactic Dynamics effects

Long-range $U(1)_D$ force $\Longrightarrow$ interactions $\chi/\bar{\chi}$

DM can change its kinetic energy via:

- Scattering
  - Hard scattering: 1 collision $\Delta v/v \sim O(1)$
  - Soft scattering: multiple collisions $\Delta v/v \sim O(1)$
- Bremsstrahlung: emission of $\hat{\gamma}$ when DM accelerates

Hard Scattering



$$V(r) = \frac{\hat{\alpha}}{r} \sim \frac{1}{2} m_\chi v^2$$

$$b_{\rm hard} = \frac{2\hat{\alpha}}{v^2 m_\chi}$$

$$\sigma_{\rm hard} \approx b_{\rm hard}^2 = \frac{4\hat{\alpha}^2}{m_\chi^2 v^4}$$

$\sigma_{\rm hard}$ increases as $v \longrightarrow 0$

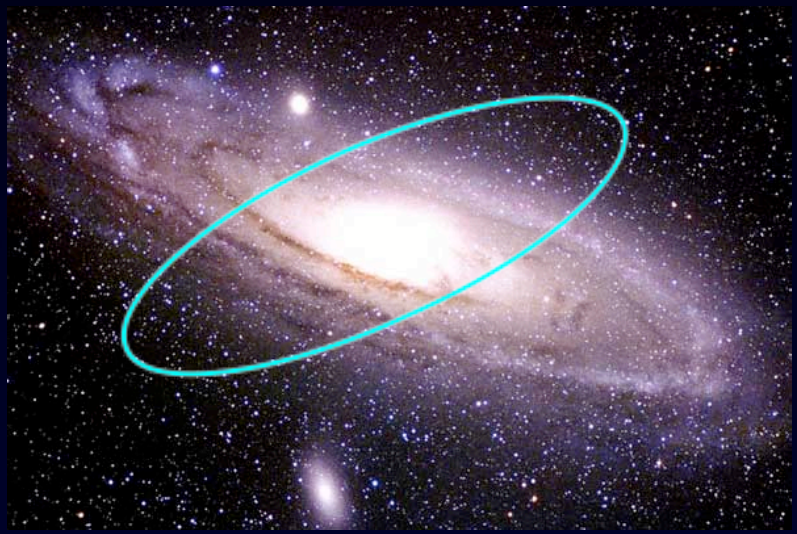
as radius at which $V(r) \propto \frac{1}{r} \sim \frac{1}{2} m_\chi v^2$ increases

Hard Scattering constraint

Average time for a hard scatter for DM is greater than the age of the Universe

$$\tau = \frac{1}{n\sigma v} \gtrsim \tau_{\rm universe}$$

For Milky Way:



$$\tau_{\rm dyn} = 2\pi R/v$$

$$\tau_{\rm universe} \sim 50\,\tau_{\rm dyn}$$

$$N \approx 10^{64}\left(\frac{m_\chi}{\rm TeV}\right)^{-1}$$

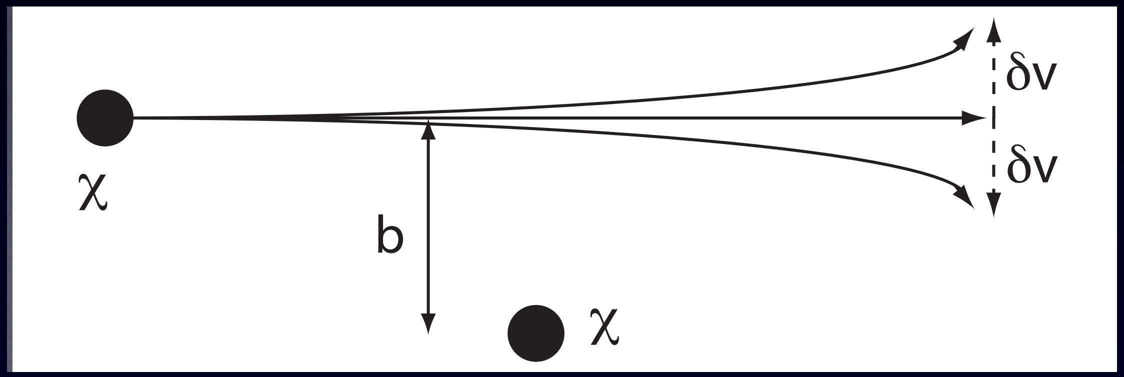
$$\frac{\tau}{\tau_{\rm dyn}} = \frac{2R^2}{3N\sigma} \gtrsim 50 \quad \Longrightarrow \quad \frac{\tau_{\rm hard}}{\tau_{\rm dyn}} = \frac{G^2 m_\chi^4 N}{6\hat{\alpha}^2} \gtrsim 50$$

$$v \simeq \sqrt{\frac{GM_{\rm Gal}}{R}}$$

Soft scattering

DM can "softly" scatter many times

- ΔKinetic E. $\sim O(1)$ when integrated over all interactions



Per approach:

$$\delta v = \frac{2\hat{\alpha}}{m_\chi b v}$$

Taking into account:

- # interactions between b and $b + \delta b$

$$\delta n = (N/\pi R^2) 2\pi b db$$

- Integrating over impact parameters

$$b_{\rm hard} < b < R$$

Δv^2 as the DM particle orbits once through the halo

$$\Delta v^2 = \frac{8\hat{\alpha}^2 N}{m_\chi^2 v^2 R^2} \ln\left(\frac{G N m_\chi^2}{2\hat{\alpha}}\right)$$

Cannot loose $\Delta v^2/v^2 \sim O(1)$ during the history of the Universe ($\tau_{\rm universe} \sim 50\,\tau_{\rm dyn}$) $\longrightarrow$ $\underset{\Delta v^2/v^2 \sim O(1)}{\text{\# orbits}} \gtrsim 50$

$$\frac{\tau_{\rm soft}}{\tau_{\rm dyn}} = \frac{G^2 m_\chi^4 N}{8\hat{\alpha}^2} \ln^{-1}\left(\frac{G N m_\chi^2}{2\hat{\alpha}}\right) \gtrsim 50$$

This is the dominating effect: due to integrating over all distances, enhanced by Coulomb log

Bremsstrahlung

DM can emit a $\hat{\gamma}$ when accelerates during a collision

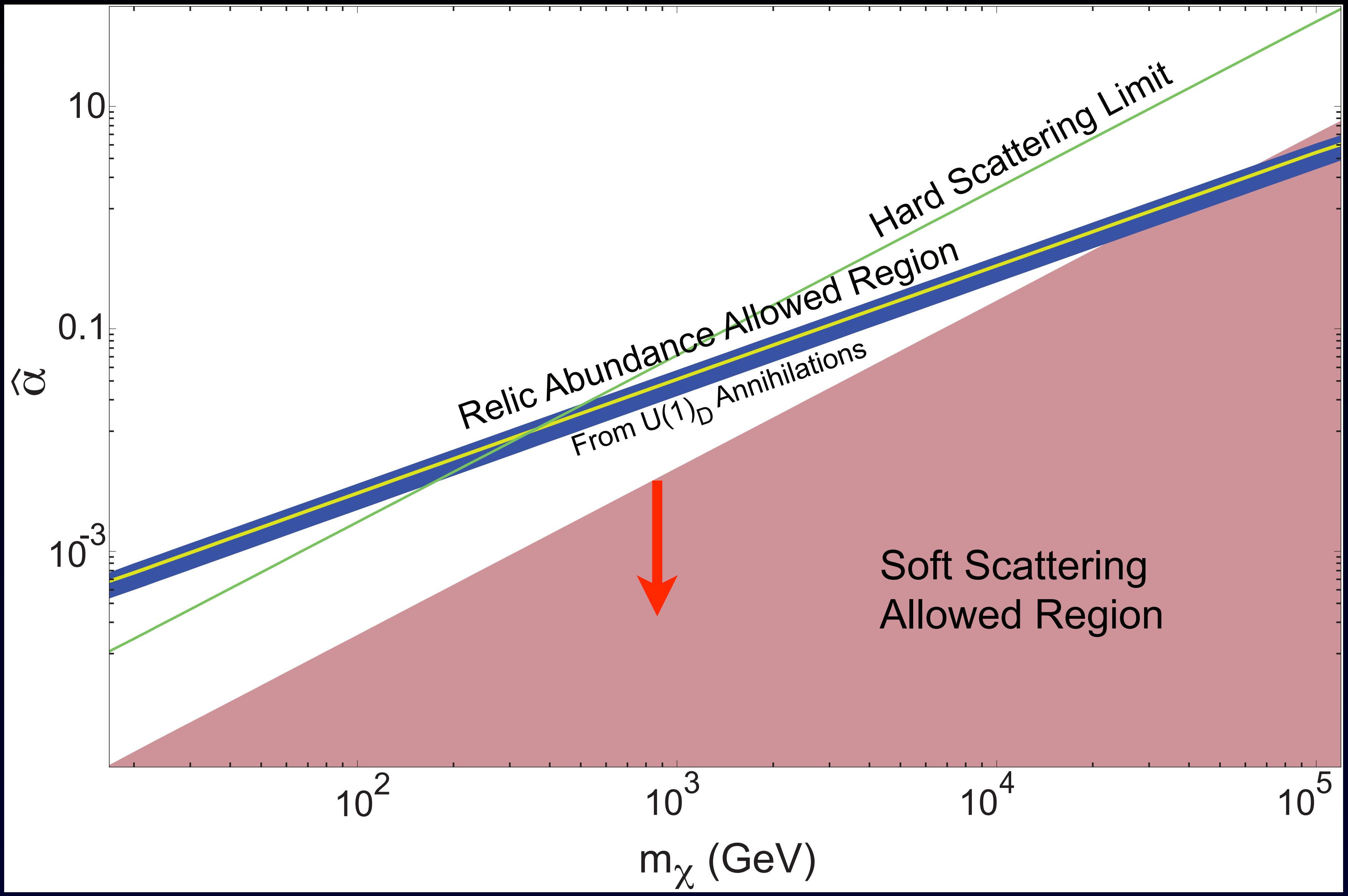
$$\frac{dEnergy}{d\omega} \propto |d(\omega)|^2 \qquad (\vec{d} = -\hat{e}\vec{r})$$

During soft collisions cannot loose $\Delta v^2/v^2 \sim O(1)$ during the lifetime of the Universe

$$\frac{3}{64}\frac{G m_\chi^3 R}{\hat{\alpha}^3} \ln^{-1}\left(\frac{G N m_\chi^2}{2\hat{\alpha}}\right) \geq 50$$

This bound is weaker than hard and soft scattering

Relic abundance and Galactic Structure



$U(1)_D$ cannot provide the correct relic abundance

$U(1)_D$ cannot provide the correct relic abundance and satisfy galactic structure

Solution: couple the dark matter to the ordinary weak interactions as well as to $U(1)_D$

- Weak interactions $\Longrightarrow$ correct relic abundance
- Scattering due to $U(1)_D \propto v^{-4}$
  - At late times becomes important

Can have correct relic abundance and

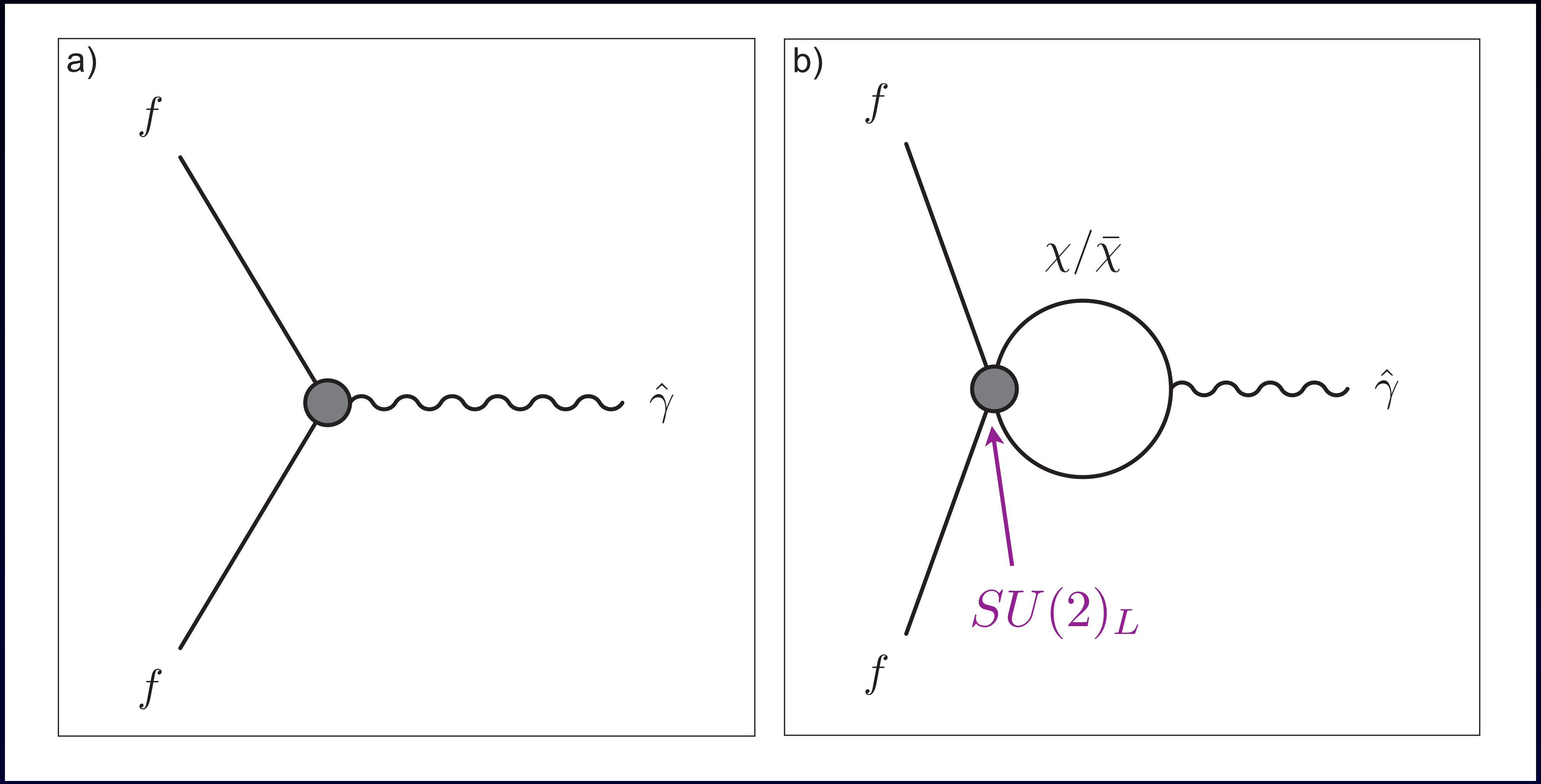
$\hat{\alpha} \lesssim 10^{-3}$ for $m_\chi \sim 1\,\mathrm{TeV}$

Bonus:

dark charge conservation ensures DM stability

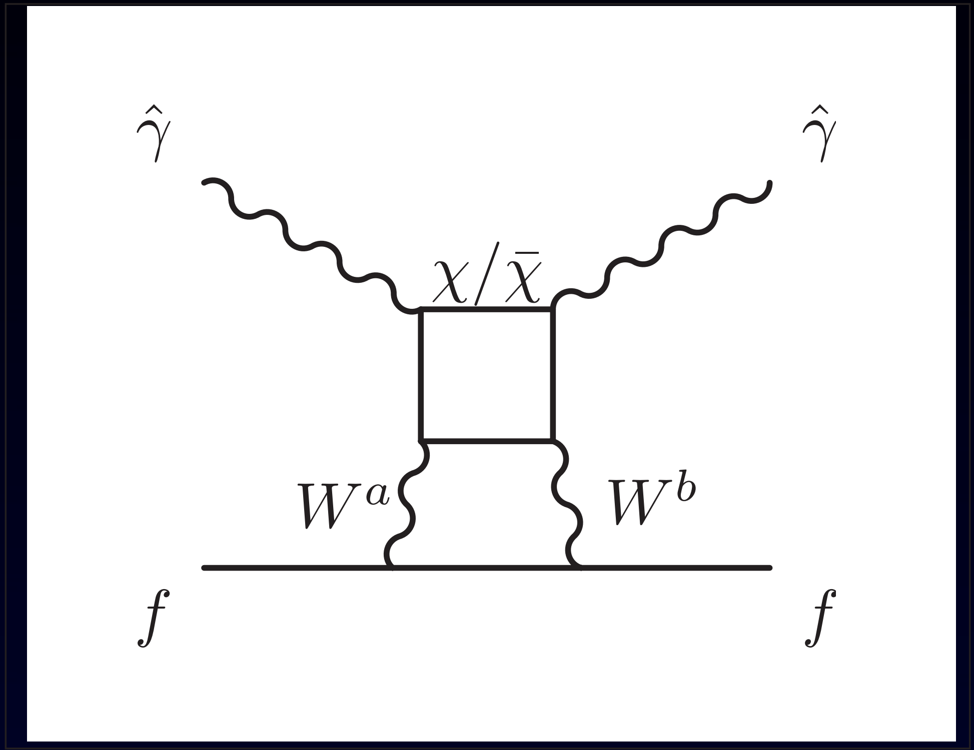
If DM couples to SM weak interactions and to dark photons, shouldn't we have detected dark photons?

Dark photons only couple directly to DM



Zero! +/- dark charge in the loop from $\chi/\bar{\chi}$

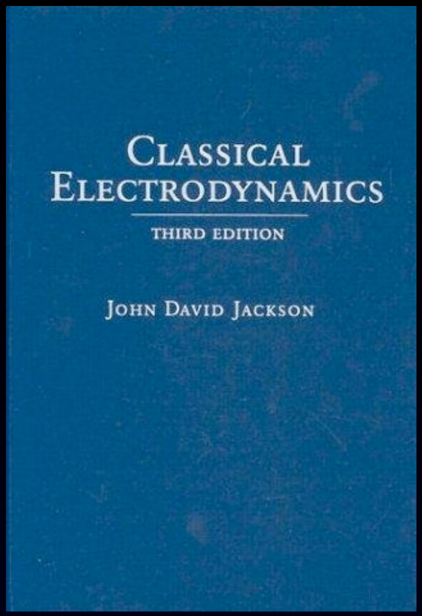
Dark photon interactions with SM fermions only at two loops



Very weak effective interaction!

- DM would look like WIMPs in direct detection experiments
- Effects of Dark Radiation could be seen in halo structure (for $\hat{\alpha}$ near soft scattering limit)

Potential Early Universe problems of Dark E&M:



1. New light particles and BBN bound

    OK-- temperature of dark background radiation is low

2. Structure Formation

    OK-- charged DM decouples from the dark background radiation very early

1. New light particles and BBN bound

$$N_\nu = 3.24 \pm 1.2\,(2\sigma)$$

From BBN bound can derive limits on particle content and dark temperature $\hat{T}$

- Define ratio $\xi(T) = \hat{T}/T$

After visible and dark sector decouple, freeze out of d.o.f causes $\xi \neq 1$

BBN bound: $g_{\text{light}}\xi(T_{\text{BBN}})^4 = \frac{7}{8} \times 2 \times (N_\nu - 3) \leq 2.52$

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- Conservation of entropy in each sector after they decouple

$$g_{\text{light}}\left[\frac{g_{\text{heavy}}+g_{\text{light}}}{g_{\text{light}}}\frac{g_{*\text{vis}}(T_{\text{BBN}})}{g_{*\text{vis}}(T_{\text{decop}})}\right]^{4/3}\xi(T_{\text{decop}})^4 \leq 2.52$$

Minimal Dark Sector: $\chi \;\; g_{\text{heavy}} = 3.5 \qquad \hat{\gamma} \;\; g_{\text{light}} = 2$

In the case of DM having weak interactions and $U(1)_D$ temperatures might track until DM freeze out

$g_{*\text{vis}} \geq 18.8$ OK as long as freeze out before QCD transition $\sim 200\text{MeV}$

2. Structure Formation

Until DM decouples from $\hat{\gamma}$ density perturbations cannot grow

Decoupling occurs when $\hat{\gamma}$ stops imparting significant velocity to DM

$$t_{\rm diss}^{-1} \equiv v^{-1}\frac{dv}{dt} = v^{-1}\frac{F}{m_\chi} = H$$

Radiation Pressure

$$F = \frac{4}{3}\hat{\sigma}_T a\hat{T}^4 v$$

Hubble time (radiation)

Thomson cross section

$$\hat{\sigma}_T = \frac{8\pi}{3}\frac{\hat{\alpha}^2}{m_\chi^2}$$

$$H^2 = \frac{4\pi^3}{45} g_* \frac{T^4}{m_{\rm Pl}^2}$$

Find

$$1 + z_* = 2.3 \times 10^{20} \xi^{-4} \left(\frac{10^{-3}}{\hat{\alpha}} \right)^2 \left(\frac{m_\chi}{\mathrm{TeV}} \right)^3 g_*(T)^{1/2} \left(\frac{g_{*S}(T)}{g_{*S}(T_0)} \right)^{2/3}$$

$\boxed{\text{Decouples very early!} \longrightarrow \text{No suppression of structure formation}}$

Interesting open question: do phenomena of "dark magnetohydrodynamics" dramatically affects the evolution of structure?

DM halos consist of $\chi/\bar{\chi}$ plasma

One possibility: Weibel (Firehose) instability

Exponential growth of magnetic fields in plasmas with a velocity anisotropy

- Velocity anisotropy when subhalos collide?
- Needs seed magnetic field

Weibel instability will affect how larger halos are constructed from the collision of smaller halos when

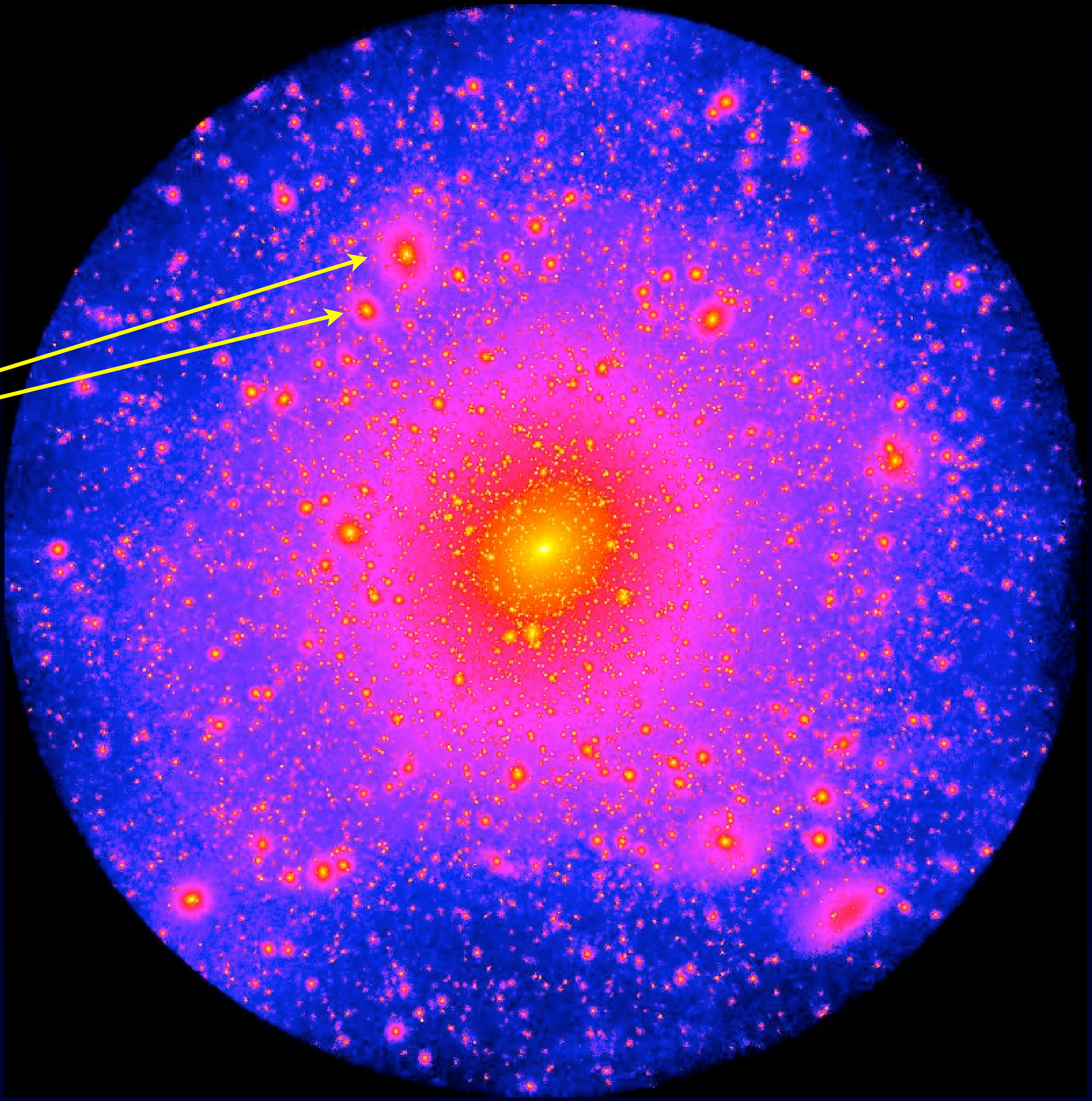
$$\tau_{\text{collision}} \sim \Gamma^{-1} \qquad \Gamma = \omega_p \frac{v}{c} = \sqrt{\frac{(4\pi)^2 \hat{\alpha} \rho}{m_\chi^2}} \frac{v}{c} \sim 10^{-2} s^{-1} \frac{\hat{\alpha}^{1/2}}{m_\chi/\text{TeV}}$$

Relevant when $$\left(\frac{m_\chi}{\text{TeV}}\right) \lesssim 10^{11} \hat{\alpha}^{1/2} \left(\frac{\tau}{10^6 \text{ yrs}}\right)$$

This is all the parameter space of interest!

The Weibel instability is very rapid on the timescales for subhalos to collide in the process of galaxy formation.

Impact?



[Quinn et al.]

Conclusions

The dark matter sector could be minimal: cold and collisionless or more complicated with the addition of long range forces

Dark electromagnetism alone cannot satisfy the observed relic abundance and galactic structure bounds

Could have DM with weak scale interactions and dark E&M. Dark E&M effects perhaps only seen through galactic dynamics

We need to understand dark magnetohydrodinamics???